Bandpass Filters
Past and Present

Bandpass filters are passive optical devices that control the flow of light. They can be used either to isolate certain wavelengths or colors, or to control the wavelengths reaching a detector. Applications range from detecting the gaseous composition of a distant star to determining the chemical activity in a human cell.

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In their earliest form, bandpass filters were constructed of absorbing media in a solute, such as water or glass. These typically have a gradual transition from low to high absorption, which limits their use in applications requiring precisely controlled wavelength bands. One is also limited by the available pigments. Absorption filters were followed by interference filters made by depositing a multilayer optical coating onto one or more transparent substrates, which produced a more highly refined transmission band surrounded by regions of low transmission.

The first interference bandpass filters transmitted 40 to 50 percent of a specific 10-nm bandwidth while blocking or attenuating all other wavelengths by a factor of $>10^4$ optical density (OD 4). Modern high-performance, all-dielectric interference filters can achieve transmission of >95 percent and attenuation of OD 10 with bandwidths less than 1 nm.

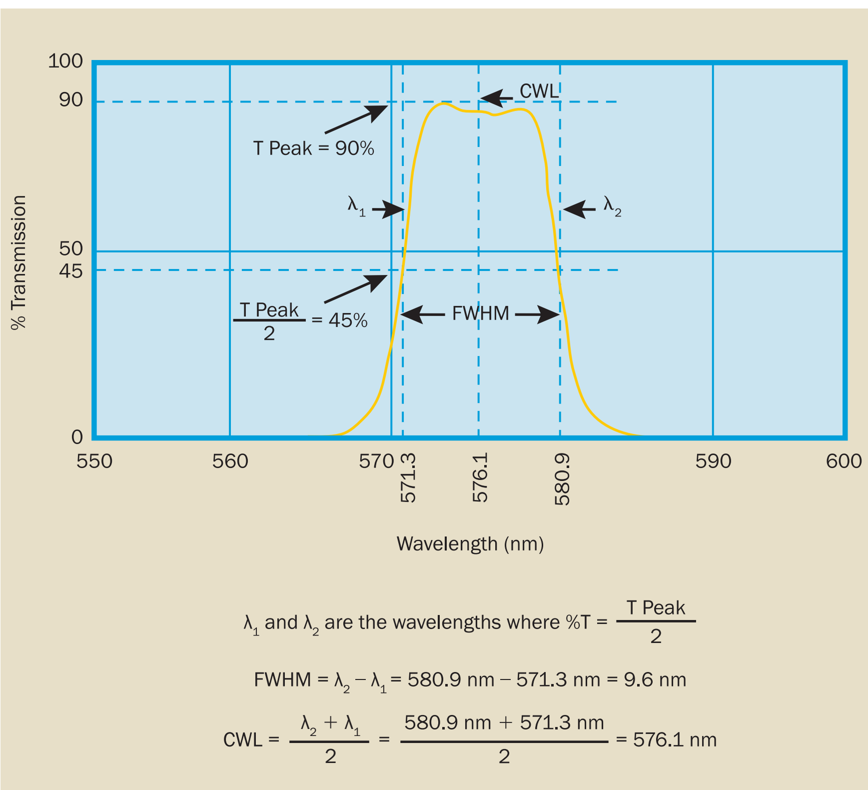

Figure 1. Fabry-Perot bandpass design showing CWL and FWHM.

Metallic bandpass filters

Early interference bandpass filters employed metallic films. To manufacture them, a metal film with high levels of reflectance and absorbance was deposited under vacuum onto a transparent substrate. When the surface of the metal is then coated with one or more dielectric thin films of appropriate thickness and refractive index, it is possible to eliminate the reflection in a specific wavelength range with a corresponding increase in transmission. Other wavelengths are unaffected and therefore continue to reflect incident energy. The result is an induced transmission bandpass filter. The constraints of these filters are limited out-of-band attenuation and limited transmission (<50%) resulting from the residual absorption of the metal thin film.

Improved attenuation and transmission can be achieved by condensing metal films onto a substrate where several metal layers are separated by nonabsorbing dielectric materials with an effective optical thickness equal to one-half the wavelength of a desired transmission band. This multilayer construction acts as a Fabry-Perot (FP) interferometer in the first order. The industry refers to this FP stack as a “cavity.” As described later, the number of cavities can be modified to generate a desired effect. Being the lowest possible order, it attenuates all longer wavelengths, and only harmonics of orders greater than one will be transmitted. Because these harmonics occur at shorter wavelengths, the filter can be combined with an absorbing filter such as colored glass that absorbs the harmonic bands, making it possible to create a single bandpass. With several metal layers, each reflecting and absorbing the spectrum both longer and shorter than the center wavelength, these bandpass filters can achieve optical density greater than five (>OD 5) in the attenuation regions while transmitting about half of the incident energy.

Dielectric FP bandpass filters

In applications such as fluorescence and Raman detection, where unwanted radiation can be 10^6 times more intense than the desired wavelength region, high-efficiency all-dielectric solutions are required. Using non-absorbing dielectric materials, it is possible to create nearly perfect dichroics – that is, reflectors that can reflect all of some wavelengths and transmit all of some other wavelengths. Up until about 10 years ago, these filters were often made of an assembly of component filters where each component produces a part of the required filtering effect. Typically, a colored glass component was used to absorb much of the unwanted energy which was combined with an interference coating, which is designed to further reflect unwanted light and to transmit the desired spectral region.

Historically, theoretical performance was limited by the need to control the deposition process dynamically at the reflected wavelength. Filter manufacturers in the past have dealt with this process control limitation by creating bandpasses based on the model of a Fabry-Perot interferometer. The FP principle states that reflection will be canceled when a standing wave exists between two reflectors. In contemporary interference filters, the interferometer uses a solid spacer layer made of nonabsorbing dielectric material. As in the case of the early FP filters made with metal reflectors, a bandpass will result at the wavelength of maximum reflectance of a stack of alternating layers of dielectric materials when a phase-inverting half-wave layer is at the center of the stack. The primary feature of this type of bandpass is that efficiency is very high with resulting transmittance at unity. A single-cavity FP filter will have a bandwidth that is determined by the degree of reflection within the FP interferometer. With reflection of 95 percent, the bandpass will be on the order of 1 nm FWHM (full-width at half

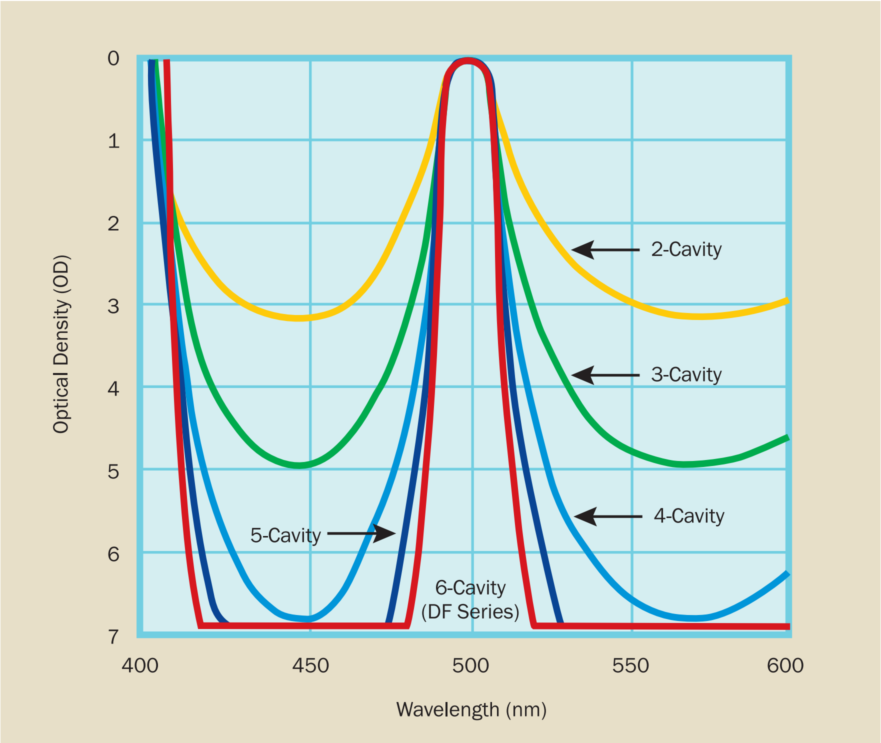

Figure 2. Fabry-Perot bandpass graph for designs with two to six cavities.

max), Figure 1. At the center of the band, the transmission will exceed 90 percent, while the attenuation outside of the bandpass is relatively narrow with a maximum attenuation of only OD3. When a wider bandpass is desired, it is achieved by reducing the reflectivity within the FP. With reflectors of 90 percent, the bandwidth would be 10 nm, but the attenuation would only be OD2. This level of attenuation is not adequate for most filter applications.

In theory, there is no limit to the degree of attenuation possible using optical interference. Light impinging on a surface coated with alternating layers of materials of different refractive indices will be reflected when each layer is of a thickness equivalent to a quarter of the wavelength (quarter wave) in question. The degree of reflection is limited only by the difference in refractive index between the materials used, the number of layers and the ability to condense specular films. Theoretical attenuation of >OD 20 can be achieved, and measured values approaching OD 10 have been reduced to practice. If the materials are selected to have very low extinction coefficients, the modeled transmission in the bandpass region can approach unity, and in practice, measures in excess of 95 percent.

Increasing the number of cavities in a design has a number of uses in the design process. A wide bandpass can be generated by increasing the number of cavities while reducing the number of layers per cavity. A reduced number of layers effectively reduces the reflectivity within each cavity and the resulting attenuation. Increasing the number of cavities brings the OD back up to the desired level while preserving the wide bandpass. As the number of cavities is increased, the shape of the transmission band becomes more rectangular (Figure 2). Keeping a large number of layers in each cavity while adding cavities allows one to design a very narrow filter with very steep edges. Typical applications that require the isolation of wavelength regions from each other – for example, differentiating fluorescence emission and excitation energy – are possible by building multilayer stacks of as many as 100 layers. These designs may be made up of 20+ cavities in series, each cavity having reflectors of only 20 to 50 percent. The resulting thin-film coating can provide greater than 90 percent transmission over a specific wavelength region, while achieving in excess of OD6+ in the reflective region.

The traditional FP bandpass filter made with dielectric interference is effective only around the region of the defined transmission band ±~20 percent (for exam-

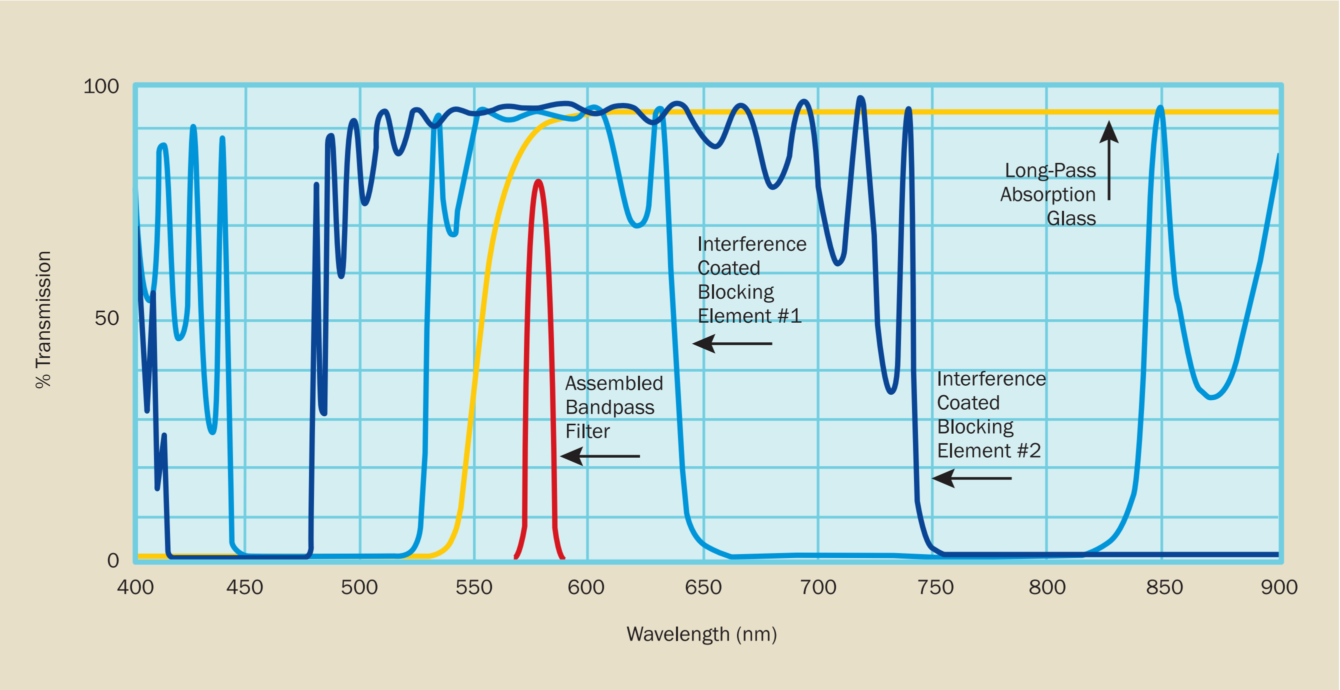

Figure 3. Bandpass filter with extended attenuation.

ple, light blue curve in Figure 3). Outside this region, the thin-film layers deviate from a phase thickness where controlled interference occurs, resulting in rapid oscillation from reflection to transmission. To extend spectral blocking, ancillary coating components are added to the assembly making up the final filter. As with any feature, there are associated costs. Extending the blocking range will make the product more expensive. Furthermore, each additional coating can add interfering reflectances. These can cause multiple images as low-level secondary reflections can be of differing path lengths (Figure 3). As described below, modern, computer-controlled coating methods largely eliminate the need for multiple components.

Angle of Incidence and polarization effects

It is important to note that the performance of a bandpass filter is a function of the conditions in which it is used. Although counterintuitive, the reflection region of an optical coating shifts to shorter wavelengths as the incidence of incoming light deviates from normal (perpendicular to the surface). This effect is significant and introduces a severe technical limitation. With the ray at 45° incidence, the reflection region is shifted by more than 10 percent of the center wavelength (CWL). If the coating in question is a bandpass coating, the performance is described as:

$$\frac{\lambda_\theta}{\lambda_0} = \frac{\sqrt{n^2 - \sin^2\theta}}{n}$$

where n is the effective index of the coating, θ is the angle of incidence, λ_θ is the principal wavelength at angle of incidence θ, λ_0 is the principal wavelength at 0° angle of incidence, and n is the effective refractive index of the coating (Figure 4).

In most applications, it is desirable to minimize the effects of incident angle. To do this, the effective refractive index of the entire stack is held to a maximum. This is achieved by designing a coating stack with the largest portion of high-index material.

In addition to the change in spectral performance as a function of the incidence angle, the performance of the coating will be different in the two planes of polarization. This difference increases as the angle deviates from normal incidence. Light in the perpendicular plane will see a bandpass that is narrower and less transmissive than the bandpass seen by light at normal incidence. Conversely, the parallel polarization will be more highly transmitted, with a wider bandwidth. These effects will contribute to a polarization bias in optical systems having a low f-number or high NA (Figure 4).

Materials for thin-film coatings

Traditional materials used in interference filters maximized the refractive index mismatch between the high-index materials and low-index materials. Maximizing this difference allows one to reduce the total number of layers in the design and ultimate thickness of the film. Some examples of these materials are zinc sulfide and cryolite. They are usually deposited with physical vapor deposition using a hot crucible, boat or filament. These early materials are easily damaged and considered "soft", so they are often embedded in epoxy with a coverslip. Semi-hard coatings such as magnesium fluoride, antimony fluoride, yttrium fluoride and germanium can be used with or without a coverslip if they are handled carefully.

Development of the e-beam as a heat source for physical vapor deposition enabled the materials to reach much higher temperatures, so oxide coatings were developed such as silicon dioxide, hafnium oxide and tantalum oxide. These more robust materials do not necessarily require the protection of coverslips, but they still don't reach the refractive index and density of bulk materials.

State-of-the-art computerized plasma-assisted reactive magnetron sputtering systems also deposit oxide materials, but sequentially, by sputtering elements

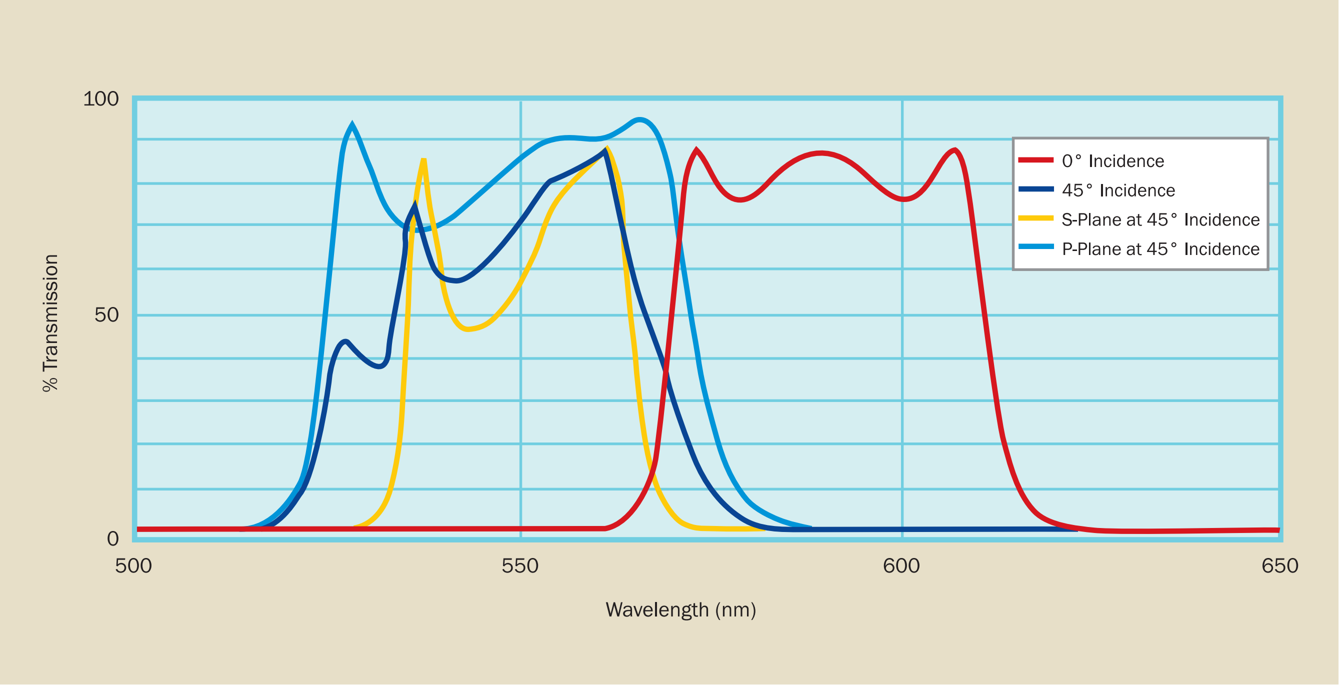

Figure 4. Bandpass filter at 0° and 45° showing s- and p-plane polarization effects.

(mostly silicon, niobium, hafnium and zirconium) followed by an oxidizing plasma. The plasma reacts with the elemental layer to form the oxide in situ, which also serves to densify the resulting films. The properties of these layers (refractive index and density) are very similar to those of the bulk materials.

The materials described thus far are strictly considered “dielectrics.” Any absorbance in the wavelengths of interest is minimal to non-existent. One can also exploit the absorbance properties of specific materials to attenuate wavelengths in certain regions. Some examples include using germanium to block visible wavelengths while designing an infrared bandpass, or similarly, a pigment to block a specific region of the visible spectrum. These types of absorbing materials run the gamut from very soft organic materials to very hard inorganic oxides.

Contemporary bandpass filters

Around the turn of the 21st century, a revolution in interference thin-film coating occurred with the implementation of computer-controlled reactive sputtering oxide systems. These systems enable much more complicated designs to be realized using very hard and durable oxide materials. While early deposition systems were hand-controlled by the operator, manufacturers were largely limited to FP designs described above. With the automated systems, the monitor wavelength can be optimized during the deposition process to facilitate non-FP designs with multiple bandpasses at non-harmonic center wavelengths and other types of designs such as spectral-shaping (i.e. solar simulator filter).

With the advancement of computing power, the limitations of design approach are reduced significantly. High-speed computers can consider the complex interrelationships of hundreds of layers. Given time and an unlimited number of iterations, the fastest computers can generate a solution for any spectral function. A complex curve can be translated to a file of intensity versus wavelength points. These points become a set of goals for the modeling software to search for matches. It is not uncommon for the solution to be a coating of several hundred discrete layers of physical thickness, ranging from a few atoms to microns. Where early filters were made as assembled components of absorbing materials/glasses and interference stacks that achieved high reflectance over defined regions, the contemporary bandpass filter can be deposited on a single side of a single substrate.

Unfortunately, the design generated is certain to be impractical to produce. A first step is to look for layers that are very thin and/or will not cause large changes in the desired end result. Not only are these layers difficult to deposit and control, but their optical constants may not follow the values used for the optimization. These layers can be selectively eliminated to determine their significance. Another dimension to the manufacturability of a design has to do with the monitoring technique. Physical thickness monitors such as resonant crystals can be used for a wide range of thicknesses, but have limited precision. The highest-precision monitors rely on real-time feedback of the optical interference effect. Obviously, this effect will vary radically over the spectral range in question. The effect of each layer on the percent transmittance or reflectance at the control wavelength is calculated to determine the curve of film thickness (time) versus %T expected during film growth. With modern computer-controlled deposition systems, monitor wavelengths can be changed between each layer to improve the accuracy. These systems are also able to adjust the deposition parameters “on the fly” if the material properties deviate from those used in the design. A typical process map includes a control matrix for each layer in the deposition. A number of monitor techniques will be identified. The technique is apt to change, depending on the other aspects of the deposition process.

These aspects include the relative position of the layer in the stack, and the conditions of the source and substrate at that point in the deposition cycle.

No matter what substrate and what coating, the physical limitations of stress and adhesion must not be exceeded. Sophisticated optics must meet both spectral requirements and physical requirements, such as transmitted wavefront distortion and/or surface flatness. Furthermore, the resulting optic must have a useful life in the expected environment and maintain the spatial expectations of the system. Inherent in the depositing of these complex stacks is the resulting development of stress in the physical optic and in the adhered film. In some cases, stress buildup can break the bond between the film and the substrate causing the film to flake off or even causing the substrate itself to break. To address these physical limitations, a cooperative approach to defining the substrate and coating must occur. Often, a second surface can be identified to help divide and balance the coating stress and thickness so as to put less demand on the stability of the substrate. For example, optimizing the design for a transmission or reflection edge instead of the center wavelength results in short- or long-pass filters that can be combined on two sides of a single substrate to give a bandpass.

With a coating design that has been optimized for spectral performance, it is possible to approach unity transmission over wide spectral bands while creating reflection of very wide spectral regions. Custom coatings can be designed to cover well over a harmonic in spectral space and five orders of magnitude in dynamic range. A typical coating of this complexity in the visible region of the electromagnetic spectrum will have a physical thickness of 10 to 22 µm. Deposition times of 5 to >20 hours are to be expected in machines that employ energetic processes to deposit refractory oxide materials.

With consideration for the complexity of the multilayer design, accentuated by the sensitivity to interactions between the coating and the substrate, it is common to do one or more test iterations to verify expectations.

The tools for depositing contemporary bandpass filters have operating costs in the range of $1,000 per hour, so it is understandable that product cost has increased dramatically over the classical approach described earlier. With larger machines, the unit cost of small parts can be very reasonable as long as the demand exceeds deposition cycle capacity.

Deposition tools for these contemporary bandpass filters are produced by a number of engineering firms. Design software is also available from a number of vendors. With the combination of this hardware and software, it is possible to create virtually any desired spectral function. Spectral shaping coatings, including bandpass and bandstop as well as dichroic designs that control both transmitted and reflected portions, can be produced from the vacuum UV to the mid-IR.